

Carbon emissions of cities from a consumption-based perspective

Zhifu Mi ^a, Jiali Zheng ^{a,b,c,*}, Jing Meng ^{d,*}, Heran Zheng ^e, Xian Li ^e, D'Maris Coffman ^a, Johan Woltjer ^f, Shouyang Wang ^{b,c}, Dabo Guan ^{e,*}

^a The Bartlett School of Construction and Project Management, University College London, London WC1E 7HB, UK

^b Academy of Mathematics and Systems Science, Chinese Academy of Sciences, Beijing, 100190, China

^c School of Economics and Management, University of Chinese Academy of Sciences, Beijing, 100190, China

^d Department of Politics and International Studies, University of Cambridge, Cambridge CB3 9DT, UK

^e Water Security Research Center, School of International Development, University of East Anglia, Norwich NR4 7TJ, UK

^f Department of Planning and Transport, Faculty of Architecture and the Built Environment, University of Westminster, London NW1 5LS, UK

Abstract: Carbon emission inventories are the foundations of climate change mitigation and adaptation in cities. In this study, we estimated production-based CO₂ emissions from fossil fuel combustion and industrial processes in eleven cities in Hebei Province of China in 2012 and used input-output theory to measure their consumption-based CO₂ emissions. By comprehensively comparing production- and consumption-based emissions, we found that six developed cities were consumption based with import-dependent trade patterns, while the five other cities were production based, mostly medium in size, with the potential to transform into consumption-based cities with socioeconomic development. Emissions embodied in imports accounted for more than half of the consumption-based emissions in most cities, which shows the significance of interregional cooperation in tackling climate change. International cooperation is also important at the city level, as international imports also impacts consumption-based emissions. From the perspective of final use, emissions caused by fixed capital formation predominated in most cities and were determined by their economic development models.

Keywords: Consumption-based accounting, production-based accounting, embodied CO₂ emissions, city, input-output model

* Corresponding authors: zhengjiali@amss.ac.cn (J. Zheng), jm2218@cam.ac.uk (J. Meng), dabo.guan@uea.ac.uk (D. Guan)

1. Introduction

Since the sharp growth of the global population and the continuous acceleration of the industrialization process in developing countries, the demand for fossil energy in human activities has increased in recent years [1, 2]. Global climate change caused by greenhouse gas emissions represented by CO₂ has become a common and serious problem faced by nations and regions around the world and is threatening human beings and the environment. Therefore, emission-reducing and energy-conserving strategies have become a worldwide consensus to respond to and mitigate global climate change. One of the most important steps is the accurate calculation of carbon emissions in various regions to clarify drivers and to allocate emission reduction responsibility to countries and economies [3]. The scientific and rational carbon emission accounting approach is a suitable basis for the determination and implementation of carbon emission reduction targets and policy formulations. At present, carbon emission accounting is still an international research hotspot, where the significant problem is how to distribute responsibilities among carbon producers and consumers.

There are two main approaches to measure carbon emissions: production-based accounting (PBA) and consumption-based accounting (CBA) [4, 5]. Currently, the most widely used carbon emission accounting approach is PBA, which calculates the carbon emissions from domestic production, including exports, in the producing process as the responsibility of the producer [6, 7]. PBA can constrain the carbon-emitting behaviour of producers and can promote producers to improve the energy efficiency of unit products. PBA can assist producers to address negative externalities. As PBA is widely applied in protocols pertaining to global climate change, many cities calculate carbon emissions from a production perspective and compile urban greenhouse gas emission inventories to be consistent with national-level accounting, which is conducive to horizontal comparison among cities. However, despite its obvious advantages, PBA does not consider the ultimate destinations and final consumers for goods and services [8]. When promoting the development of the global economy through trade redistributions [9, 10], producers and consumers of commodities will also be geographically separated due to trades, resulting in interregional emission transfer; thus, part of the emission-reducing responsibilities within borders are passed on to other areas [11-13]. By excluding indirect emissions, PBA cannot depict the overall picture of urban greenhouse gas emissions [14]. If direct carbon emissions are fully borne

by exporting countries, it will be clearly unfair, and CO₂ emissions will not be effectively reduced [15]. Similarly, under PBA, cities with low production but high consumption in China tend to be considered low-carbon [16]. The failure to include indirect emissions will lead essentially to unfair assignments of emission reduction tasks, will further affect global emission reduction efficiency, and may even adversely affect active participation in reducing emissions. Consequently, the shift of carbon emission accounting from PBA to CBA has gradually received attention from the academy [17-19].

Compared to PBA, CBA calculates the total carbon emissions of final products including imports, where the responsibility for carbon emissions is borne by consumers [20]. This approach attributes direct emission responsibilities to the final consuming sectors; consequently, it characterizes the impact of human consumption choices on climate change. First, its main advantage is to reduce carbon leakages among cities and encourage spill-overs of emission-reducing technologies [21]. In addition, the index of emission per capita according to CBA more realistically reflects CO₂ emission responsibilities of urban residents. At the policy level, this approach encourages public consumption which is resource-saving by receiving goods and services through the public sector, curbs private consumption with high emission intensity, promotes the purchase of products and services from cleaner production areas, and greens the entire supply chain of urban products [22]. At present, research on global carbon emissions and related issues based on CBA focuses on the CO₂ emission-reducing responsibilities of regions under the CBA system [23-25]. As global carbon emissions calculated by CBA are also increasing annually [26], it is particularly important to analyse global carbon emissions and their influential factors according to CBA. In general, the above studies of CBA based on the input-output analysis are relatively advantageous [21, 27], as they not only contribute to a deep understanding of the influence on regional carbon emissions accounting by interregional trades but also provide an important theoretical basis to fairly and reasonably allocating responsibilities and analysing the role of carbon transfer in global climate governance.

A large number of studies have explored the feasibility of using CBA to calculate carbon emissions and determine national emission responsibilities, to analyse consumption-based carbon emissions at both global and national levels. At the global level, research has studied emission characteristics triggered by multinational trades [28, 29]. At the national level, consumption-based

carbon emissions have been assessed in many countries, such as Australia [30], China [31, 32], Italy [33], Japan [34], Spain [35], Turkey [36], and the UK [37]. However, with the rapid growth of China's urban population, rapid industrialization and urbanization have led to an increasing demand for energy, causing a significant amount of greenhouse gas emissions [38]. Thus, cities are crucial to implementing carbon emission mitigation policies in China. Studies on emission inventories at the city level are limited, and mostly focus on PBA [39, 40]. Only a few studies have investigated consumption-based cities [41-43]. For example, Hasewaga [44] found that emissions calculated based on PBA were significantly different from those based on CBA in Japan. Feng [45] studied four megacities in China using CBA and found that urban consumption resulted in high emissions in surrounding areas through interregional trades. Given the reflections above, this study compares CBA and PBA among cities from the perspective of carbon emission accounting to fill a research gap on the position of CBA at the city level. The focus is specifically on cities in China.

Although more research has shifted the focus to the city level, the paper specifically presents a coherent sample from the same province, offering relatively useful data compared to irregularly distributed city data in China. This province is key for China's economic transformation to address climate change. From the current urbanization and industrialization in China, energy conservation and emission reductions have achieved remarkable achievements with declining urban energy consumption and industrial emissions [46]. As a major industrialized province in China, Hebei is under considerable pressure with respect to emission reductions; the large-scale development and transformation of energy resources in this province have promoted rapid economic growth but have also led to a continuous increase in carbon emissions. The increasing carbon emissions in Hebei Province, as a typical energy-consuming province in China, are closely related to rapid economic development and changing energy consumption structures. More specifically, the demand for primary energy is still high in Hebei Province, which is now in the stage of rapid development of industrialization and urbanization. Hence, it is essential to improve the structure of consumption and upgrade industrial technology to control the carbon emissions of this province. Simultaneously, the development level and industrial degree of different cities in Hebei Province vary widely, resulting in different levels of energy consumption and carbon emissions among cities.

This paper closes the research gaps from the following aspects. First, with the rapid development of the urbanization, cities are crucial to mitigate carbon emissions [47]. However, studies on emission inventories based on CBA at the city level are limited [48], especially in China [49]. This study analyses carbon emissions of cities from a consumption-based perspective. In addition, given the data availability, most studies focus on selected cities which lose the whole picture of a province [50], while this paper uses data from each city in Hebei Province. In summary, addressing an emerging agenda of previous research, this study aims to analyse carbon emissions in urban China. The focus is on cities in Hebei province, and an analysis of CBA compared to PBA, thereby providing a scientific basis for strengthening carbon emission management and formulating emission reduction policies.

2 Method and data

2.1 Consumption-based carbon emission accounting

As the input-output (IO) model quantifies the network and relationship among industries in the national economy by collecting currency transactions of sectors, it has been widely applied with expansions across various aspects [51, 52], including CO₂ emissions [53-55], energy consumption [56-58], resource use [59-61] and other environmental studies [62-64]. [Consumption-based carbon emissions can be accounted by the IO model](#). Specifically, carbon emissions directly or indirectly embodied in the final goods and services consumed are estimated by CBA. In terms of environmental accounting, exogenous transactions expressed as emissions or energy are exchanged among each national sector and represent the direct and indirect consumption of products from different industries embodied in the final demand. In this study, PBA is first measured from energy consumption and industrial processes in Chinese cities [43, 65]. CBA is based on the following relationship: “CBA = consumption-based emissions from local production + emissions embodied in imports (domestic & international) = production-based emissions - emissions embodied in exports (domestic & international) + emissions embodied in imports (international & domestic)”, which shows that the import and export commodities play an important role in quantifying real emissions [66].

The basic framework of the input-output theory was developed by Wassily Leontief in the quantitative input and output analysis of the economic system in the late 1930s [67]. To estimate

CBA at the city level, the standard environmentally extended input-output method is applied in this study, using the fundamental equation known as the Leontief equation:

$$X = (I - A)^{-1} F \quad (1)$$

where X denotes the total output vector of x_i representing the output of economic sector i ; F denotes the final demand vector of f_i including the domestic use and international export of sector i ; I is the identity matrix; A is the technical coefficient matrix showing the inter-sectoral flows; and $(I - A)^{-1}$ is the Leontief inverse matrix.

To evaluate CBA, the calculation of CO₂ emissions embodied in the final demand requires the emission intensity vector E , which is composed of the coefficient that indicates the CO₂ emissions per unit of industrial output e_i in economic sector i ; thus, the CO₂ emissions in CBA can be estimated as follows [68, 69]:

$$C = E(I - A)^{-1} \hat{F} \quad (2)$$

where C denotes the vector of total CO₂ emissions embodied in the end-use products, $E = [e_1 e_2 \dots e_n]$ represents the row vector of emission intensity associated with each industry sector, and $\hat{F} = \text{diag}(F)$ means that \hat{F} is the diagonal vector of F [6].

Although C is calculated based on the total emissions embodied in the final demand, it cannot separate local production and outside imports. Because detailed import-related data are not available, the information obtained at the national level is used to estimate the CO₂ emissions embodied in imports, which are briefly described as:

$$C^{im} = E^{im} (I - A^{im})^{-1} \hat{F}^{im} \quad (3)$$

where C^{im} denotes the vector of total CO₂ emissions embodied in the import including both domestic and international imports, E^{im} represents the row vector of the national emission intensity, A^{im} is the technical coefficient matrix adjusted by the import share, F^{im} is the import, and $\hat{F}^{im} = \text{diag}(F^{im})$ indicates that \hat{F}^{im} is the diagonal vector of F^{im} . Similarly, the information at the national level is used to estimate the CO₂ emissions embodied in domestic and international exports. Given the availability of data, emissions caused by residential energy consumption are

not considered in this study.

2.2 Data sources

In this study, in which the CBA is calculated for eleven cities in Hebei Province, China, three sets of data are mainly used, i.e., input-output tables, populations and CO₂ emissions of cities. The input-output tables at the city level are obtained from regional statistics bureaus. Population data are derived from the database of the National Bureau of Statistics of China [70]. Data on carbon emissions are not officially released in China, and the data quality of cities is relatively poor except for megacities. Consequently, a method to construct a production-based CO₂ emissions inventory for cities in China is developed in this study according to the definition provided by the IPCC territorial emission accounting approach [71, 72]. There are 9 primary industry products, 20 energy types and 47 socioeconomic sectors in each inventory. [The concordance of 45 sectors \(excluding the urban and rural\) in emission inventory data and 42 sectors in the IO table is shown in Table S1 in supplementary information.](#)

All the imports including domestic and international imports are from IO tables. In the IO table, there is a sum relation that for a specific sector, its “intermediate output + final demand - net imports = total output”. Therefore, the domestic and international import data are included in the IO table. Details for the IO layout could be found in WIOD [73]. The IO tables at the city level are from local bureau of statistics [74-77]. By aggregating the CO₂ emissions from different fossil fuels and sectors, we obtained the total CO₂ emissions. All data are sourced from China Emission Accounts and Datasets, which is a free China energy data sharing platform [78].

In IO analysis, there are several assumptions: (1) it assumes that same quantity of inputs is needed per unit of output, regardless of the level of production; (2) it assumes fix input structure which means any change in output would not change the input structure; (3) the model assumes that an industry uses the same technology to produce each of its products; (4) it assumes static model which means no price would change. The CO₂ emission intensity in this paper uses survey based on a study [79] instead of IPCC default data [80], which can increase the accuracy of results. Because of assumptions in IO analysis, all products in one sector are treated as homogeneity, which means different products in one sector are treated same. This can lead to the aggregation error, where different products in one sector can be different in terms of emissions. Although it

may have some uncertainty in the results because this is the endogenous assumption, the production-based emissions are distributed into each production process in IO technique. Thus, the total emission can be constrained and results can be accepted.

3. Results and Discussion

3.1 Consumption-based emissions for eleven cities in Hebei, China

The compositions and causes of consumption-based emissions in eleven cities in Hebei, China, were analysed. These varied across cities but showed certain regional and structural characteristics.

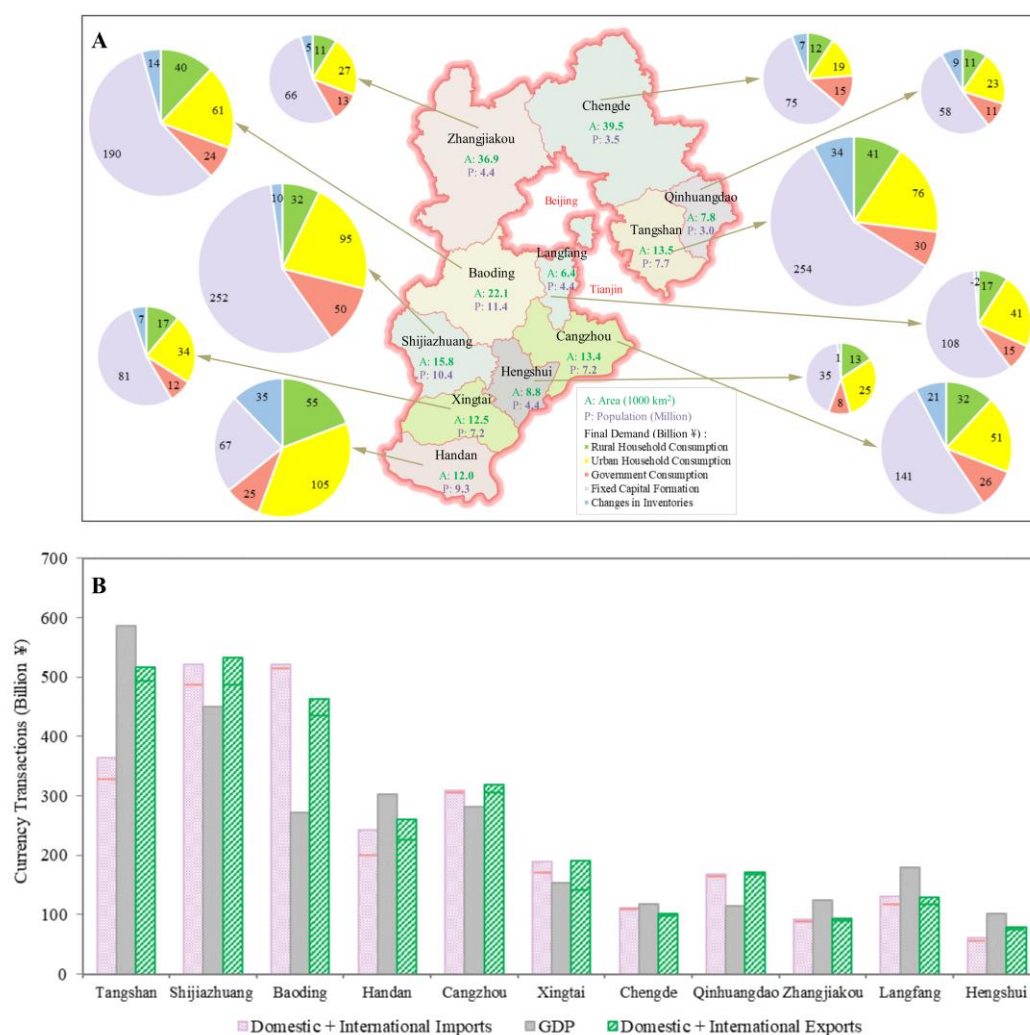


Fig. 1. (A) Socioeconomic information for eleven cities in Hebei in 2012. *A* represents the area of each city (in 1000 km²). *P* denotes the population of each city (in millions). Total final demands are shown in the pie charts (in billion ¥), with the five colours representing rural household consumption, urban household consumption, government consumption, fixed capital formation and changes in inventories. (B) GDP and trade in monetary units for eleven cities in Hebei in 2012. Total imports (left), GDP

(middle) and exports (right) are shown in the bar charts (in billion ¥), with both domestic (bottom) and international (top) transactions.

Although the population density in central and southern Hebei is relatively high, with two cities in the north sparsely populated, the final demand structure with the largest contribution by fixed capital formation was similar for each city in 2012 except the southernmost, Handan (**Fig. 1A**). The population density is related to the geographic location. Cities with the lowest population density in Hebei are northern cities, Chengde (89 persons/km²) and Zhangjiakou (119 persons/km²). This is attributed to their areas being ranked first and second and is also likely because Chengde and Zhangjiakou are bordered by Liaoning Province to the northeast and Inner Mongolia Province to the northwest, respectively, where relatively poor economic performance and massive migration in recent years affects social development and living conditions. In contrast, Baoding and Langfang benefit from geographical advantages. The former has the largest population (11 million) as a result of connecting the capital Beijing to the provincial capital Shijiazhuang, and the latter, located between two municipalities (Beijing and Tianjin) has the second largest population density (691 persons/km²). Additionally, there is a clear relationship between the demand structure and the population density. The savings rate in China has been high for a long time, which makes investment rather than consumption a major driver of domestic demand [81]. Therefore, most cities in Hebei are characterized by the capital formation accounting for the largest proportion at an average of 55% of the final demand, followed by urban consumption and then government and rural consumptions. However, the largest percentage of the final demand in Handan is urban household consumption (105 billion ¥, 36%) rather than fixed capital formation (67 billion ¥, 23%). Handan ranked first by population density (774 persons/km²) in Hebei.

GDP, domestic plus international imports and exports for eleven cities in Hebei in 2012 were analysed by classifying them into different types (**Fig. 1B**). The top two cities with the highest GDP were the industrial centre Tangshan (586 billion ¥) and the provincial capital Shijiazhuang (450 billion ¥), while the city with the lowest GDP was Hengshui (101 billion ¥). However, the GDP in the above three cities approximately doubled compared with that in 2007 [43]. Because the population remained almost unchanged, the GDP per capita in Tangshan (76,000 ¥/person) was also the highest, followed by the relatively developed cities Shijiazhuang (43,000 ¥/person)

and Langfang (40,000 ¥/person). By comparing their final demand with their imports, cities were classified into an external-dependent type with the former lower than the latter represented by Baoding and Qinhuangdao and an internal-oriented type with greater final demand represented by Tangshan and Langfang. In terms of imports and exports, currency transactions in imports and exports were similar in most cities with a few exceptions. For example, Baoding is a typical import-dependent city (521 billion ¥), while Tangshan is a typical export-oriented city (517 billion ¥). Specifically, areas with better industrial systems had international imports occupying more than 5%, including Tangshan (10%), Shijiazhuang (7%), Handan (18%), Xingtai (9%) and Langfang (11%). Simultaneously, domestic imports in less developed regions far exceeded international imports, which accounted for no more than 2%, including Baoding (2%), Cangzhou (1%), Chengde (0.1%), Qinhuangdao (1%), Zhangjiakou (0.5%) and Hengshui (2%).

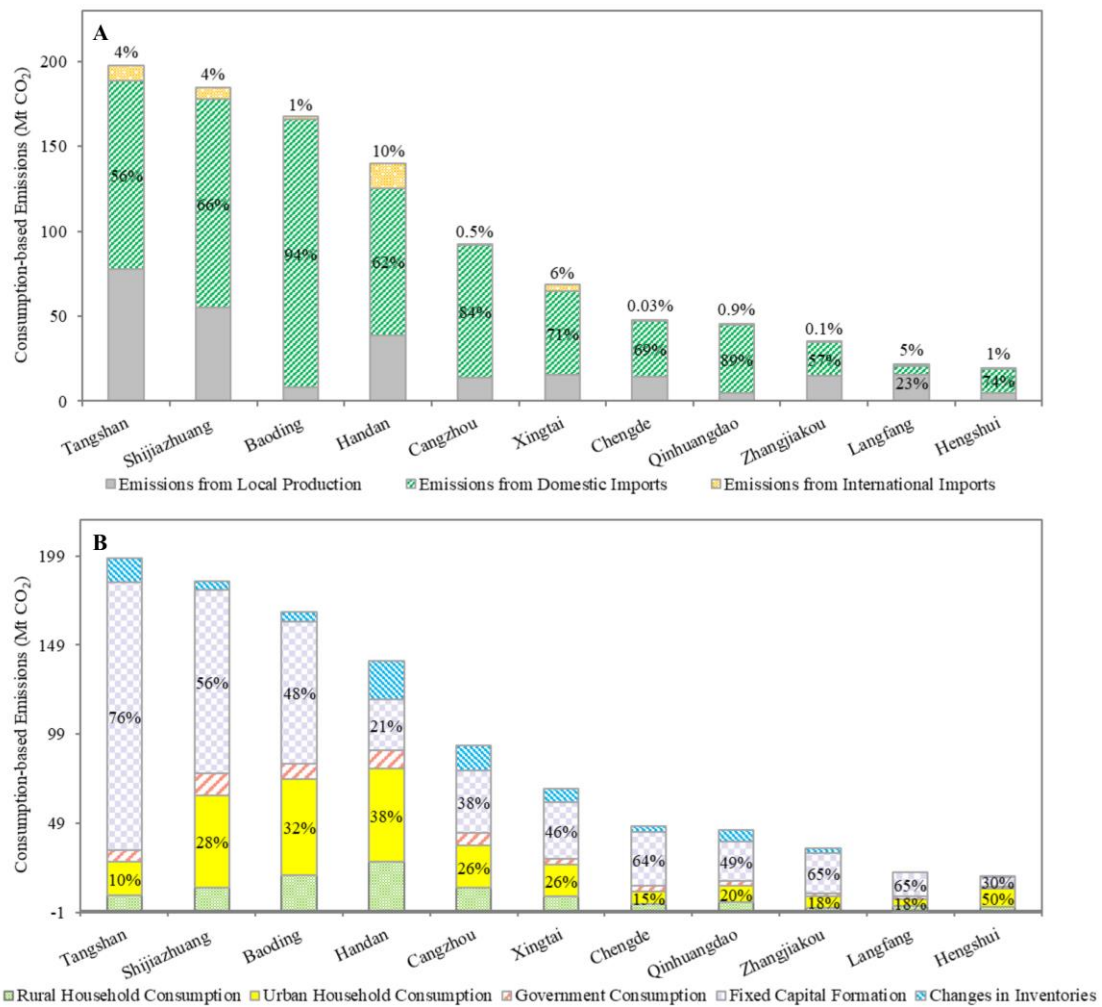


Fig. 2. (A) Consumption-based emissions from local production, domestic imports and international imports in eleven cities of Hebei in 2012. The percentages of emissions embodied in domestic and

international imports are shown inside and above the bars respectively. (B) Consumption-based emissions for five final demand categories for eleven cities in Hebei in 2012. The percentages of emissions embodied in urban household consumption and fixed capital formation are shown at the bottom and top of the bars, respectively.

The emissions caused by domestic and international imports in each city in 2012 accounted for a large percentage of total consumption-based emissions, including emissions embodied in total imports and emissions attributed to the consumption of local products (**Fig. 2A**). From the perspective of an absolute amount, consumption-based emissions varied widely among cities in the same province and were affected by the final consumption and imports mentioned above. Compared with the smallest emitter Hengshui (19 Mt CO₂), Tangshan ranked first (198 Mt CO₂), with approximately 10 times the consumption-based emissions of Hengshui. Furthermore, products imported from elsewhere in China and foreign countries might result in higher emissions compared with products produced and consumed within city boundaries. For instance, imports into Qinhuangdao were 18% higher than those into Langfang, resulting in two-fold higher emissions in Qinhuangdao (45 Mt CO₂) compared with Langfang (22 Mt CO₂), and the total consumption in Qinhuangdao (280 billion ¥) was lower than that in Langfang (310 billion ¥). From the perspective of relative proportion, import-embodied emissions in 2012 were far higher than self-produced emissions in most cities. In 10 cities of Hebei, only with the exception of Langfang, more than 50% of consumption-based emissions were attributed to imports from external regions at home and abroad, which indicates that consumption relied heavily on foreign products as opposed to local products. The above results are consistent with previous studies on cities that showed approximately 70% CO₂ emissions in China were attributed to imports [43], and 40%-80% in Japan [44]. According to the analysis of socioeconomic information, Baoding (95%) and Qinhuangdao (90%), the two top-ranked cities in terms of proportion of imported emissions, corresponded with their external-dependent types, as imported consumption exceeded final demand. Similarly, Langfang (28%) and Tangshan (60%) accounted for the minimum percentages of imported emissions because they are typical internal-oriented type cities. Imports, as a driver of consumption-based emissions, can be further divided into domestic and international imports, which would lead to different import-emitting structures. Corresponding with the analysis above, international-imported emissions accounted for at least 4% in cities in which international

imports dominated, including Tangshan (4%), Shijiazhuang (4%), Handan (10%), Xingtai (6%) and Langfang (5%), while fewer imports from abroad resulted in emissions from international imports that did not exceed 1%, i.e., Baoding (1%), Cangzhou (0.5%), Chengde (0.03%), Qinhuangdao (0.9%), Zhangjiakou (0.1%) and Hengshui (1%). Hence, with a considerable contribution from emissions embodied in international imports, it is important to strengthen international cooperation at the city level.

Similarly, the emissions caused by fixed capital formation in each city in 2012 accounted for a large percentage of total consumption-based emissions in the five final demand categories, including rural household consumption, urban household consumption, government consumption, fixed capital formation and changes in inventories (**Fig. 2B**). The maximum proportion of emissions was driven by capital formation, followed by urban household consumption, in most cities in Hebei with the top three being Tangshan (76%), Zhangjiakou (65%) and Langfang (65%), which reveals that the demand relied heavily on investment as opposed to consumption. The above results are consistent with other research on CO₂ emissions in China [43, 82-84], where development models including rapid but insufficient economic growth associated with domestic demand, as well as extensive urbanization and government-led stimulus policies are the reasons for the largest contribution from capital investment. However, Handan and Hengshui were exceptions, as urban household consumption contributed more than capital formation consumption. Specifically, urban households emitted more (38%) than capital formation (21%) in Handan based on its final demand structure mentioned above, while proportions ranked differently for emissions and final demand in Hengshui mainly because of its industrial consumption structure. In Hengshui, the emissions caused by urban consumption (50%) accounted for more than those from capital formation (30%); however, the urban consumption percentage (30%) of the final demand was lower than that of capital formation (43%). An underlying explanation is that the industrial sectors with high emissions intensity consumed more, but invested less. To provide a clear explanation, Hengshui is compared with Handan, which shows a similar structure in terms of emission proportions. Hengshui is famous for education, with highly reputed schools, and the urban household consumption exceeded the normal level in education-related industries, including several high-emission intensity sectors (“papermaking, printing and manufacture of articles for culture, education and sports activities”, “manufacture of communication equipment, computer

and other electronic equipment”, “production and supply of electric power and heat power”, and “education”), which led to more emissions for the same amount of total urban consumption. However, capital formation did not occur in sectors with high emission intensity (“processing of timbers and manufacture of furniture”, “manufacture of nonmetallic mineral products”, “manufacture of metal products”, “scrap and waste”, etc.), resulting in a significant reduction in emissions from investment in these sectors.

3.2 Consumption-based and production-based emissions of eleven cities

Following the relationship “local-produced emissions = CBA - imported emissions (domestic & international) = PBA - exported emissions (domestic & international)”, emissions from consumption of imports and production of exports for eleven cities in Hebei, China, were compared.

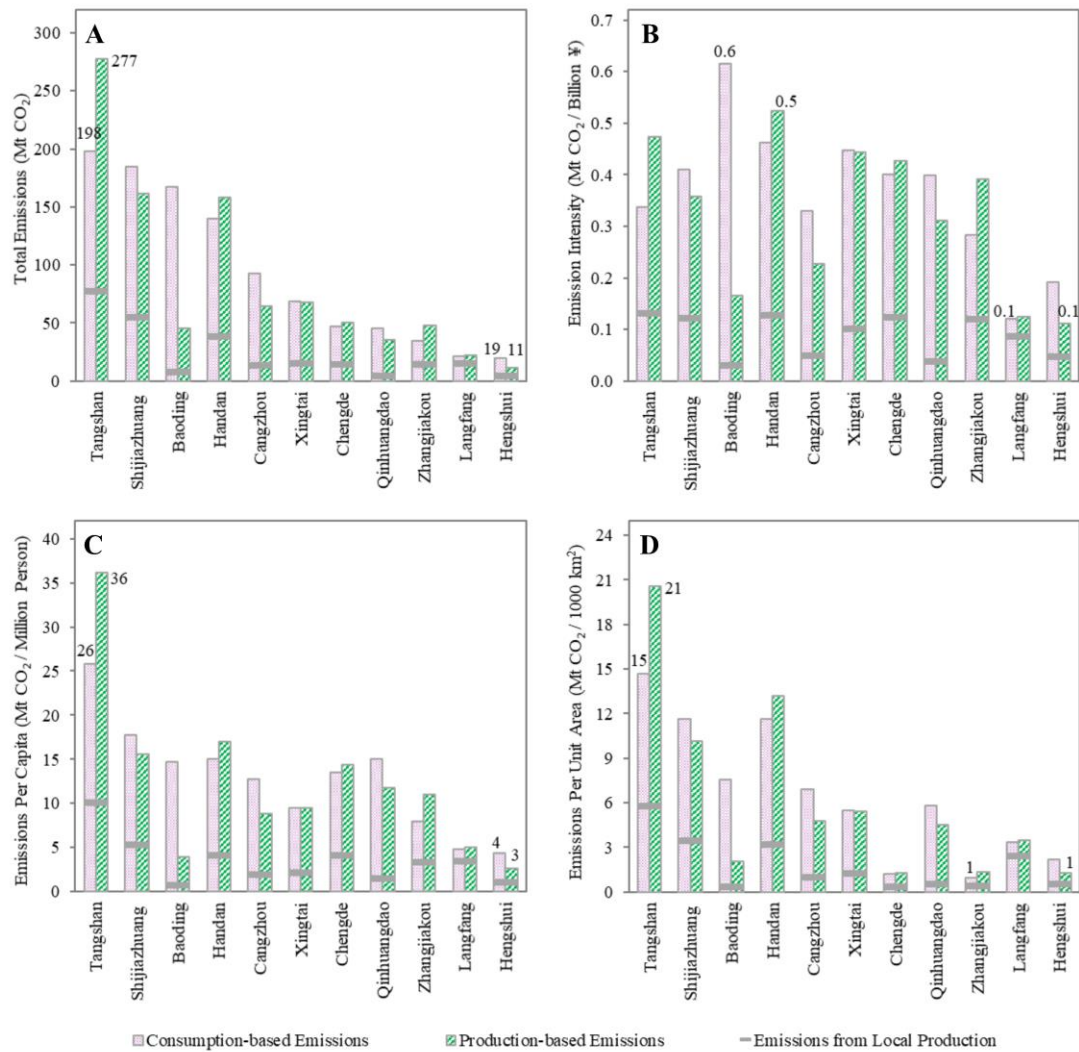


Fig. 3. (A) Total consumption-based emissions, production-based emissions and emissions from local

production at the city level in Hebei in 2012. The highest and lowest emissions associated with consumption and production are shown above the respective bars. (B) Consumption-based, production-based and locally produced emission intensity for eleven cities in Hebei in 2012. (C) Consumption-based, production-based and locally produced emissions per capita in eleven cities of Hebei in 2012. (D) Consumption-based, production-based and locally produced emissions per unit area for eleven cities in Hebei in 2012.

Cities in Hebei were categorized into consumption-based cities and production-based cities with large differences in the source of emissions (**Fig. 3A**), which were mainly caused by the trade pattern and emission intensity [85, 86]. Shijiazhuang, Baoding, Cangzhou, Xingtai, Qinhuangdao and Hengshui were classified as consumption-based cities and had consumption-based emissions higher than production-based emissions. According to the above two reasons, Baoding, as a typical import-dependent city analysed in 3.1, was classified as a consumption-based type, mainly due to its trade pattern, with emissions from consumption (168 Mt CO₂) almost four times higher than the amount of production-based emissions (45 Mt CO₂). In addition, Qinhuangdao, as an example of a city with similar imports and exports, was classified as a consumption-based city with higher emissions from consumption (45 Mt CO₂) than from production (35 Mt CO₂) because of its high emission intensity of imports (0.4 Mt CO₂/billion ¥). Production-based cities with higher emissions from exports than from imports included Tangshan, Handan, Chengde, Zhangjiakou and Langfang. The typical export-oriented trade pattern led to production-based emissions (277 Mt CO₂) being larger than consumption-based emissions (198 Mt CO₂) in Tangshan, and Zhangjiakou, with similar imports and exports, emitted more from production (48 Mt CO₂) than from consumption (35 Mt CO₂), caused by the high emission intensity of exports (0.4 Mt CO₂/billion ¥). Furthermore, the findings reveal a large gap between CBA and PBA, which demonstrates that PBA benefited consumption-based cities in allocating responsibilities. Thus, production-based cities have proposed widespread application of CBA for climate change mitigation. Notably, the five production-based cities in Hebei mentioned in the results are consistent with the conclusion that most medium-sized cities are production-based cities [43]. In addition, the result of using cities that exhibit both similarities and differences within one province as good examples indicating that most developed cities in China are consumption-based cities, according to [43], was expanded to both developed and less developed regions. In fact, the former

was proved to be caused by the predominant import trade pattern, while the latter mostly imported consumption-based products with a high emission intensity, which might be due to unimproved technology or primary industries. Shijiazhuang transformed from a production-based city in 2007 to a consumption-based city in 2012 due to its rapid economic development as the provincial capital of Hebei, which provides evidence of the inference made in [43].

The difference in total production-based emissions between the highest emitter Tangshan (277 Mt CO₂) and the lowest emitter Hengshui (11 Mt CO₂) was approximately 25-fold, which was higher than that of consumption-based emissions (10 times higher). However, only Hengshui (0.1 Mt CO₂/billion ¥) retained at the same ranking for production-based emission intensity, and Langfang (0.1 Mt CO₂/billion ¥) replaced Hengshui with the lowest consumption-based emission intensity. Baoding (0.6 Mt CO₂/billion ¥) and Handan (0.5 Mt CO₂/billion ¥) ranked first in consumption- and production-based emission intensity, respectively (**Fig. 3B**). Adjusted by per unit GDP, the differences among cities in consumption-based, production-based and local produced emissions decreased. The emission intensity of local production was divided into two groups by approximately 0.1 (Mt CO₂/billion ¥) or less, which indicated that the supply-demand structure was similar, and the socioeconomic development was balanced in each city of Hebei. In addition to the efficiency adjustment of GDP, the remaining two emissions intensities of imports and exports were also affected by the sectoral consumption structure and industrial technology level. In terms of emissions per capita, with an even population distribution in Hebei, the rankings of three cities in the north, i.e., Chengde, Qinhuangdao and Zhangjiakou, with relatively sparse populations increased slightly compared with total emissions (**Fig. 3C**). Similarly, with regard to emissions per unit area, the large area of Zhangjiakou resulted in the smallest consumption-based emissions per unit area, with the rankings of Tangshan and Hengshui retained (**Fig. 3D**). Hence, different accounting approaches with various criteria should be integrated into policies pertaining to emission reduction.

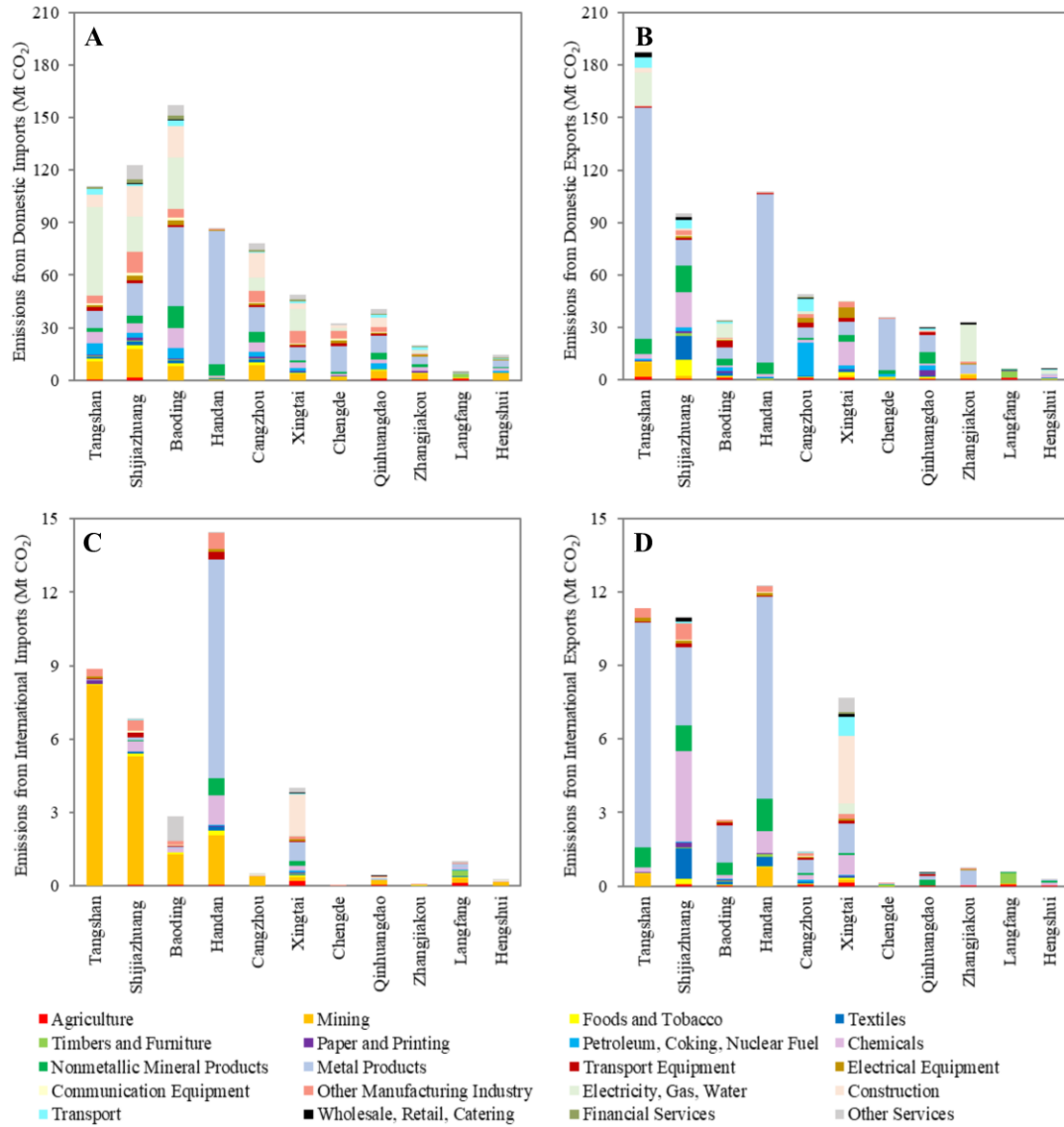


Fig. 4. (A) CO₂ emissions embodied in domestic imports by sector for eleven cities in Hebei in 2012. (B) CO₂ emissions embodied in domestic exports by sector for eleven cities in Hebei in 2012. (C) CO₂ emissions embodied in international imports by sector for eleven cities in Hebei in 2012. (D) CO₂ emissions embodied in international exports by sector for eleven cities in Hebei in 2012.

Emissions embodied in imports and exports were determined by the volume of imports and exports and the consumption structure; higher emissions were caused by increasing consumption in sectors with a high emission intensity. The domestic imports of Baoding (512 billion ¥) resulted in the highest emissions from domestic imports (157 Mt CO₂), while emissions embodied in domestic imports of Chengde (33 Mt CO₂) were almost 7 times the amount of Langfang (5 Mt CO₂), and its domestic imports (112 billion ¥) were slightly lower than those of Langfang (116 billion ¥) (**Fig. 4A**). Emissions embodied in domestic exports of the largest emitter, Tangshan (188

Mt CO₂), were significantly higher than those of Shijiazhuang (95 Mt CO₂); domestic exports ranked first in the former (494 billion ¥) followed closely by the latter (486 billion ¥). This might be caused by the historic heavy industrial system in Tangshan compared with Shijiazhuang with its upgraded industrial structure in the period 2007-2012 (**Fig. 4B**). Handan was ranked first in emissions from international imports (14 Mt CO₂) due to the highest level of these imports (43 billion ¥). Emissions embodied in the international imports of Tangshan (9 Mt CO₂) were slightly higher than those of Shijiazhuang (7 Mt CO₂), contrary to domestic imports, and this corresponded with the international imports of the former (36 billion ¥) and the latter (35 billion ¥) due to the similar structure of sectoral consumption (**Fig. 4C**). In contrast to the findings above, sectors in Xingtai produced lower emissions associated with international exports, with the system focusing on tertiary industry, although this city had the highest level of international exports. Handan, Tangshan and Shijiazhuang were the top three emitters in terms of international exports due to their massive emissions from sectors represented by metal products (**Fig. 4D**).

In general, the metal product sector contributed the most to emissions, which is consistent with previous research [43]. Therefore, Hebei still needs to improve technology, upgrade industry, and transform the structure. A vertically comparison of domestic and international emissions indicated that total domestic imports and exports were much higher than the total international values. Moreover, domestic emissions in each city decreased successively, while international emissions were concentrated in the maximum and minimum extremes with a sizeable gap in the centre. A horizontally comparison of imported and exported emissions indicated that the relative size of total imports and exports corresponded to the type of city, i.e., consumption based or production based. As most cities in Hebei have a secondary industrial system, the proportion of emissions from the tertiary industry related to imports was higher than that related to exports. More specifically, emissions from domestic and international imports varied widely among sectors; emissions from domestic imports were mostly embodied in electricity, gas, water and metal sectors, while emissions from international imports were mainly embodied in mining. This is because goods and services from other domestic regions generally indicate China's industrial characteristics and technical level according to the comparative advantage. However, products from other countries abroad will show large differences compared to domestic products. Although there were different structures of emissions at home and abroad in the import sectors, emissions

from domestic and international exports were similar in structure, i.e., both concentrate in metal products. This is a result of exporting products from advantageous industries based on the factor endowment.

4. Conclusions

A key suggestion from the analysis is that different emission accounting approaches have a strong influence on issues of allocating responsibilities to mitigate climate change. In the analysis, CO₂ emissions of eleven cities in Hebei, China, were measured by CBA compared with PBA to supplement mitigation policies. Based on different consumption structures, including final demand plus domestic and international imports, cities not only emit carbon within boundaries but also absorb carbon through interregional trade. The final demand is relatively high in internal-oriented cities with self-produced consumption, which, in turn, is associated with population density affected by geographical location. For instance, urban consumption may exceed capital investment in final demand due to a large population density. In addition, the consumption structure will also influence external-dependent cities, which are divided into export-oriented and import-dependent types, including domestic and international imports by sectors with CO₂ from different energy uses. According to a range of socioeconomic factors, different drivers cause different compositions of emissions across cities.

With respect to consumption-based emissions, imported emissions from domestic and international goods and services in ten cities (excluding Langfang) in 2012 are much higher than self-produced emissions embodied in local products, accounting for typically more than 50% of consumption-based emissions attributed to imports from external regions at home and abroad. From the perspective of the imported proportions in emissions, consumption at the city level is mostly determined by goods and services from other regions and foreign countries rather than local products. Therefore, both national systems in China and global mechanisms among economies are generally established through policies aimed at strengthening cooperation between carbon-consuming and carbon-producing regions for climate change mitigation. In terms of consumption-based emissions caused by trade within national borders, in the Chinese case a national emissions trading scheme (ETS) has been established based on trial transactions among carbon trading system pilots. This scheme has coordinated production relations, balanced emission shares, strengthened synergistic effects, and mitigated aggregate changes in China. In addition, the

interregional clean development mechanism (CDM) in China will promote cities or provinces with cleaner production to buy carbon emission permits by investing in less developed regions or areas for improved technologies and upgraded industries. Furthermore, the design and operation of mechanisms in developed economies, represented by the European Union Emissions Trading System (EU ETS), have been advanced by improvement with extensive practice, and those mechanisms play an important role in coordinating global actions of carbon emissions and climate change among countries. Excellent mechanisms should not only be used as references and examples of best practice, but should also establish active and widely distributed involvement. From the perspective of international cooperation, interregional organizations have been addressing climate change mitigation through multilateral frameworks at the city level. For instance, the Local Governments for Sustainability (ICLEI), representing more than 20% of the world's urban population, has connected more than 1500 cities in 86 countries through a global committee. The C40 Cities Climate Leadership Group (C40), with more than 80 megacities covering more than 600 million people and 25% of the global economy, is aimed at a sustainable and low-carbon network of cities.

The emissions caused by fixed capital formation in most cities in Hebei in 2012 account for the largest proportion, followed by urban consumption and then government and rural consumptions in terms of total consumption-based emissions, which shows that the demand is predominantly driven by investment rather than consumption in China due to a high savings rate. Taking Hebei as an example, compositions of emissions were determined by the structures of the both final demand and industrial consumption in China; cities emit less by consuming or investing in sectors with a low emission intensity. By encouraging demand and accelerating urbanization, the final demand structure in China will shift from capital investment and rural consumption to urban household consumption. Simultaneously, the consumption structure in China will likely transition from high-emission intensity sectors to low-carbon industries with technical and model improvements in economic development.

By comparing emissions from imports, exports and local production for eleven cities in Hebei, cities in China can be categorized as consumption- and production-based cities depending on the source of emissions. Because trade pattern and emission intensity are the main causes of the different types, six consumption-based cities, Shijiazhuang, Baoding, Cangzhou, Xingtai,

Qinhuangdao and Hengshui, are deemed typical import-dependent cities or those with a high emission intensity from imports. This finding reveals that both developed and less developed cities in China might be consumption-based cities. However, production-based cities in China are mostly medium-sized. Examples from the Hebei case include Tangshan, Handan, Chengde, Zhangjiakou and Langfang. The above five cities are typical export-oriented types with high emission intensities from exports. Taking Shijiazhuang as an example, production-based cities would transform into consumption-based cities in the process of their socioeconomic development from medium-sized cities to metropolises. Notably, an increasing number of regions and economies have made efforts to promote the improvement of emission accounting approaches by comprehensively considering CBA and PBA with reference to various criteria based on GDP, capita or area to fairly allocate responsibilities.

In general, the activity of reducing emissions is closely related to industry upgrades and structural transformation in China because cities emit less by importing or exporting in sectors with low emission intensities. For instance, the metal product sector in Hebei contributed the most to emissions from imports and exports. Hence, technology improvement in these sectors plays a significant role in supplementing mitigation policies. In summary, global climate governance should determine emission reduction targets and formulate relevant systematic policies based on scientific and various emission accounting approaches, including indirect emissions. Simultaneously, it is necessary to make cities and regions more accountable for indirect emissions and establish matching interregional cooperation in emission reduction schemes and mechanisms to coordinate carbon consumption and carbon emissions. Additionally, regions need to improve their own development models through technology, industry and structure to reduce emissions within boundaries.

Acknowledgements

This study was supported by the National Key R&D Program of China (2016YFA0602604), the Natural Science Foundation of China (71761137001, 41629501), the UK Economic and Social Research Council (ES/L016028/1), the Natural Environment Research Council (NE/N00714X/1) and a British Academy Grant (AF150310).

References

- [1] Wrigley E. Energy and the Industrial Revolution in England. Cambridge: Cambridge University Press; 2010.
- [2] Stern DI, Kander A. The role of energy in the industrial revolution and modern economic growth. *The Energy Journal*. 2012;125-52.
- [3] Kagawa S, Suh S, Hubacek K, Wiedmann T, Nansai K, Minx J. CO₂ emission clusters within global supply chain networks: Implications for climate change mitigation. *Global Environmental Change*. 2015;35:486-96.
- [4] Shigeto S, Yamagata Y, Ii R, Hidaka M, Horio M. An easily traceable scenario for 80% CO₂ emission reduction in Japan through the final consumption-based CO₂ emission approach: A case study of Kyoto-city. *Applied Energy*. 2012;90:201-5.
- [5] Zhang B, Qiao H, Chen Z, Chen B. Growth in embodied energy transfers via China's domestic trade: Evidence from multi-regional input-output analysis. *Applied energy*. 2016;184:1093-105.
- [6] Peters GP. From production-based to consumption-based national emission inventories. *Ecological economics*. 2008;65:13-23.
- [7] Guan D, Meng J, Reiner DM, Zhang N, Shan Y, Mi Z, Shao S, Liu Z, Zhang Q, Davis SJ. Structural decline in China's CO₂ emissions through transitions in industry and energy systems. *Nature Geoscience*. 2018;1.
- [8] Steininger K, Lininger C, Droege S, Roser D, Tomlinson L, Meyer L. Justice and cost effectiveness of consumption-based versus production-based approaches in the case of unilateral climate policies. *Global Environmental Change*. 2014;24:75-87.
- [9] Lin B, Sun C. Evaluating carbon dioxide emissions in international trade of China. *Energy policy*. 2010;38:613-21.
- [10] Chen G, Wiedmann T, Wang Y, Hadjikakou M. Transnational city carbon footprint networks-Exploring carbon links between Australian and Chinese cities. *Applied energy*. 2016;184:1082-92.
- [11] Weber CL, Matthews HS. Embodied environmental emissions in US international trade, 1997-2004. ACS Publications; 2007.
- [12] Scott K, Barrett J. An integration of net imported emissions into climate change targets. *Environmental Science & Policy*. 2015;52:150-7.
- [13] Arce G, López LA, Guan D. Carbon emissions embodied in international trade: The post-China era. *Applied energy*. 2016;184:1063-72.
- [14] Hoornweg D, Sugar L, Trejos Gomez CL. Cities and greenhouse gas emissions: moving forward. *Environment and Urbanization*. 2011;23:207-27.
- [15] Davis SJ, Caldeira K. Consumption-based accounting of CO₂ emissions. *Proceedings of the National Academy of Sciences*. 2010;107:5687-92.
- [16] Feng K, Davis SJ, Sun L, Li X, Guan D, Liu W, Liu Z, Hubacek K. Outsourcing CO₂ within China. *Proceedings of the National Academy of Sciences*. 2013;110:11654-9.
- [17] Yang Z, Wei T, Moore J, Chou J, Dong W, Dai R, Yang S, Ban J. A new consumption-based accounting model for greenhouse gases from 1948 to 2012. *Journal of Cleaner Production*. 2016;133:368-77.
- [18] Hu Y, Lin J, Cui S, Khanna NZ. Measuring urban carbon footprint from carbon flows in the global supply chain. *Environmental science & technology*. 2016;50:6154-63.

- [19] Meng J, Mi Z, Yang H, Shan Y, Guan D, Liu J. The consumption-based black carbon emissions of China's megacities. *Journal of Cleaner Production*. 2017;161:1275-82.
- [20] Wiedmann T. A review of recent multi-region input-output models used for consumption-based emission and resource accounting. *Ecological Economics*. 2009;69:211-22.
- [21] Peters GP, Hertwich EG. Post-Kyoto greenhouse gas inventories: production versus consumption. *Climatic Change*. 2008;86:51-66.
- [22] Larsen HN, Hertwich EG. Identifying important characteristics of municipal carbon footprints. *Ecological Economics*. 2010;70:60-6.
- [23] Du H, Guo J, Mao G, Smith AM, Wang X, Wang Y. CO₂ emissions embodied in China-US trade: Input-output analysis based on the emergy/dollar ratio. *Energy Policy*. 2011;39:5980-7.
- [24] Wu R, Geng Y, Dong H, Fujita T, Tian X. Changes of CO₂ emissions embodied in China-Japan trade: drivers and implications. *Journal of Cleaner Production*. 2016;112:4151-8.
- [25] Jayanthakumaran K, Liu Y. Bi-lateral CO₂ emissions embodied in Australia-China trade. *Energy Policy*. 2016;92:205-13.
- [26] Xu Y, Dietzenbacher E. A structural decomposition analysis of the emissions embodied in trade. *Ecological Economics*. 2014;101:10-20.
- [27] Steininger KW, Lininger C, Meyer LH, Muñoz P, Schinko T. Multiple carbon accounting to support just and effective climate policies. *Nature Climate Change*. 2016;6:35.
- [28] Peters GP, Minx JC, Weber CL, Edenhofer O. Growth in emission transfers via international trade from 1990 to 2008. *Proceedings of the national academy of sciences*. 2011;201006388.
- [29] Meng J, Mi Z, Guan D, Li J, Tao S, Li Y, Feng K, Liu J, Liu Z, Wang X. The rise of South–South trade and its effect on global CO₂ emissions. *Nature communications*. 2018;9:1871.
- [30] Wood R, Dey CJ. Australia's carbon footprint. *Economic Systems Research*. 2009;21:243-66.
- [31] Tian X, Chang M, Lin C, Tanikawa H. China's carbon footprint: a regional perspective on the effect of transitions in consumption and production patterns. *Applied energy*. 2014;123:19-28.
- [32] Su B, Huang H, Ang B, Zhou P. Input–output analysis of CO₂ emissions embodied in trade: the effects of sector aggregation. *Energy Economics*. 2010;32:166-75.
- [33] Mongelli I, Tassielli G, Notarnicola B. Global warming agreements, international trade and energy/carbon embodiments: an input–output approach to the Italian case. *Energy policy*. 2006;34:88-100.
- [34] Nansai K, Kagawa S, Kondo Y, Suh S, Inaba R, Nakajima K. Improving the completeness of product carbon footprints using a global link input-output model: the case of Japan. *Economic Systems Research*. 2009;21:267-90.
- [35] Sánchez-Chóliz J, Duarte R. CO₂ emissions embodied in international trade: evidence for Spain. *Energy Policy*. 2004;32:1999-2005.
- [36] Tunç GI, Türüt-Aşık S, Akbostancı E. CO₂ emissions vs. CO₂ responsibility: an input-output approach for the Turkish economy. *Energy Policy*. 2007;35:855-68.
- [37] Barrett J, Peters G, Wiedmann T, Scott K, Lenzen M, Roelich K, Le Quéré C. Consumption-based GHG emission accounting: a UK case study. *Climate Policy*. 2013;13:451-70.
- [38] Wei Y, Liu L, Wu G, Zou L. *Energy economics: CO₂ emissions in China*: Springer Science & Business Media; 2011.
- [39] Dhakal S. Urban energy use and carbon emissions from cities in China and policy implications. *Energy policy*. 2009;37:4208-19.
- [40] Creutzig F, Baiocchi G, Bierkandt R, Pichler P-P, Seto KC. Global typology of urban energy use

and potentials for an urbanization mitigation wedge. *Proceedings of the National Academy of Sciences*. 2015;112:6283-8.

[41] Fan J, Guo X, Marinova D, Wu Y, Zhao D. Embedded carbon footprint of Chinese urban households: structure and changes. *Journal of cleaner Production*. 2012;33:50-9.

[42] Minx J, Baiocchi G, Wiedmann T, Barrett J, Creutzig F, Feng K, Förster M, Pichler P-P, Weisz H, Hubacek K. Carbon footprints of cities and other human settlements in the UK. *Environmental Research Letters*. 2013;8:035039.

[43] Mi Z, Zhang Y, Guan D, Shan Y, Liu Z, Cong R, Yuan X-C, Wei Y-M. Consumption-based emission accounting for Chinese cities. *Applied energy*. 2016;184:1073-81.

[44] Hasegawa R, Kagawa S, Tsukui M. Carbon footprint analysis through constructing a multi-region input-output table: a case study of Japan. *Journal of Economic Structures*. 2015;4:5.

[45] Feng K, Hubacek K, Sun L, Liu Z. Consumption-based CO₂ accounting of China's megacities: the case of Beijing, Tianjin, Shanghai and Chongqing. *Ecological Indicators*. 2014;47:26-31.

[46] Mi Z, Zheng J, Meng J, Shan Y, Zheng H, Ou J, Guan D, Wei YM. China's energy consumption in the new normal. *Earth's Future*. 2018.

[47] Long Y, Yoshida Y. Quantifying city-scale emission responsibility based on input-output analysis - Insight from Tokyo, Japan. *Applied Energy*. 2018;218:349-60.

[48] Li JS, Zhou H, Meng J, Yang Q, Chen B, Zhang Y. Carbon emissions and their drivers for a typical urban economy from multiple perspectives: A case analysis for Beijing city. *Applied Energy*. 2018;226:1076-86.

[49] Xiao H, Ma Z, Mi Z, Kelsey J, Zheng J, Yin W, Yan M. Spatio-temporal simulation of energy consumption in China's provinces based on satellite night-time light data. *Applied Energy*. 2018;231:1070-8.

[50] Liu L, Huang G, Baetz B, Zhang K. Environmentally-extended input-output simulation for analyzing production-based and consumption-based industrial greenhouse gas mitigation policies. *Applied Energy*. 2018;232:69-78.

[51] Minx JC, Wiedmann T, Wood R, Peters GP, Lenzen M, Owen A, Scott K, Barrett J, Hubacek K, Baiocchi G. Input-output analysis and carbon footprinting: an overview of applications. *Economic Systems Research*. 2009;21:187-216.

[52] Wiedmann T. Carbon footprint and input-output analysis-an introduction. Taylor & Francis; 2009.

[53] Su B, Ang B. Input-output analysis of CO₂ emissions embodied in trade: a multi-region model for China. *Applied Energy*. 2014;114:377-84.

[54] Mi Z-F, Pan S-Y, Yu H, Wei Y-M. Potential impacts of industrial structure on energy consumption and CO₂ emission: a case study of Beijing. *Journal of Cleaner Production*. 2015;103:455-62.

[55] Yan J, Zhao T, Kang J. Sensitivity analysis of technology and supply change for CO₂ emission intensity of energy-intensive industries based on input-output model. *Applied energy*. 2016;171:456-67.

[56] Yuan C, Liu S, Xie N. The impact on chinese economic growth and energy consumption of the Global Financial Crisis: An input-output analysis. *Energy*. 2010;35:1805-12.

[57] Cellura M, Di Gangi A, Longo S, Orioli A. An Italian input-output model for the assessment of energy and environmental benefits arising from retrofit actions of buildings. *Energy and Buildings*. 2013;62:97-106.

[58] Wei Y-M, Mi Z-F, Huang Z. Climate policy modeling: an online SCI-E and SSCI based literature review. *Omega*. 2015;57:70-84.

[59] Weinzettel J, Hertwich EG, Peters GP, Steen-Olsen K, Galli A. Affluence drives the global

- displacement of land use. *Global Environmental Change*. 2013;23:433-8.
- [60] Yu Y, Hubacek K, Feng K, Guan D. Assessing regional and global water footprints for the UK. *Ecological Economics*. 2010;69:1140-7.
- [61] Wiedmann TO, Schandl H, Lenzen M, Moran D, Suh S, West J, Kanemoto K. The material footprint of nations. *Proceedings of the National Academy of Sciences*. 2013;201220362.
- [62] Lenzen M, Moran D, Kanemoto K, Foran B, Lobefaro L, Geschke A. International trade drives biodiversity threats in developing nations. *Nature*. 2012;486:109.
- [63] Lin J, Pan D, Davis SJ, Zhang Q, He K, Wang C, Streets DG, Wuebbles DJ, Guan D. China's international trade and air pollution in the United States. *Proceedings of the National Academy of Sciences*. 2014;111:1736-41.
- [64] Yang S, Fath B, Chen B. Ecological network analysis of embodied particulate matter 2.5-A case study of Beijing. *Applied energy*. 2016;184:882-8.
- [65] Mi Z, Meng J, Zheng H, Shan Y, Wei Y-M, Guan D. A multi-regional input-output table mapping China's economic outputs and interdependencies in 2012. *Scientific data*. 2018;5:180155.
- [66] Rocco MV, Colombo E. Evaluating energy embodied in national products through Input-Output analysis: Theoretical definition and practical application of international trades treatment methods. *Journal of cleaner production*. 2016;139:1449-62.
- [67] Leontief WW. Quantitative input and output relations in the economic systems of the United States. *The review of economic statistics*. 1936:105-25.
- [68] Mi Z, Meng J, Guan D, Shan Y, Song M, Wei Y-M, Liu Z, Hubacek K. Chinese CO₂ emission flows have reversed since the global financial crisis. *Nature communications*. 2017;8:1712.
- [69] Mi Z, Meng J, Green F, Coffman DM, Guan D. China's "exported carbon" peak: patterns, drivers, and implications. *Geophysical Research Letters*. 2018;45:4309-18.
- [70] NBSC. National data. 2015;<<http://data.stats.gov.cn/english/>> [accessed 2015-02-01].
- [71] Mi Z-F, Wei Y-M, He C-Q, Li H-N, Yuan X-C, Liao H. Regional efforts to mitigate climate change in China: a multi-criteria assessment approach. *Mitigation and Adaptation Strategies for Global Change*. 2017;22:45-66.
- [72] Shan Y, Guan D, Liu J, Liu Z, Liu J, Schroeder H, Chen Y, Shao S, Mi Z, Zhang Q. CO₂ emissions inventory of Chinese cities. *Atmos Chem Phys*. 2016.
- [73] WIOD. World Input-Output Database. 2016;<<http://www.wiod.org/home>>.
- [74] Bureau HS. Hebei 2012 city input-output table. 2015;<<http://www.hetj.gov.cn/>>.
- [75] Statistics SMBo. Shijiazhuang: Hebei Statistics Bureau. 2015;<<http://www.sjztj.gov.cn/>>.
- [76] Yu X, Zhang M. Decomposition of factors influencing carbon emissions in the region of Beijing-Tianjin-Hebei, based on the perspective of terminal energy consumption. *Chinese Journal of Population Resources and Environment*. 2014;12:338-44.
- [77] Cong J, Liu Q, Kang J, Li W, Wang X, Li M. Analysis of interprovincial trade embodied carbon emissions in Beijing-Tianjin-Hebei and surrounding provinces: based on constructed MRIO Model. *Chinese Journal of Population Resources and Environment*. 2017;15:71-9.
- [78] CEADs. China Emission Accounts and Datasets. 2018;<<http://www.ceads.net/>>.
- [79] Liu Z, Guan D, Wei W, Davis SJ, Ciais P, Bai J, Peng S, Zhang Q, Hubacek K, Marland G. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. *Nature*. 2015;524:335.
- [80] Hajer MA. A media storm in the world risk society: enacting scientific authority in the IPCC controversy (2009-10). *Critical policy studies*. 2012;6:452-64.

- [81] Narayan PK. The saving and investment nexus for China: evidence from cointegration tests. *Applied economics*. 2005;37:1979-90.
- [82] Peters GP, Weber CL, Guan D, Hubacek K. China's growing CO₂ emissions a race between increasing consumption and efficiency gains. ACS Publications; 2007.
- [83] Guan D, Peters GP, Weber CL, Hubacek K. Journey to world top emitter: An analysis of the driving forces of China's recent CO₂ emissions surge. *Geophysical Research Letters*. 2009;36.
- [84] Feng K, Siu YL, Guan D, Hubacek K. Analyzing drivers of regional carbon dioxide emissions for China: A structural decomposition analysis. *Journal of Industrial Ecology*. 2012;16:600-11.
- [85] Jakob M, Marschinski R. Interpreting trade-related CO₂ emission transfers. *Nature Climate Change*. 2013;3:19.
- [86] López L-A, Arce G, Zafrilla J. Financial crisis, virtual carbon in global value chains, and the importance of linkage effects. The Spain-China case. *Environmental science & technology*. 2013;48:36-44.